Master's Thesis

A CMOS Indirect Time of Flight Sensor with Reset Noise Suppression

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Abstract

Image sensors especially 3-transistor image sensor and I-ToF image sensor have been suffered from the reset noise which is represented as kTC noise. Due to their operational properties, the reset noise is always remained in photodiode or FD nodes.

Even such reset noise from the conventional reset operation can affect the quality of image. In 3-transitor image sensor, the output image with the conventional reset operation of 3-T image sensor shows noise on the image itself and that is getting worsen under the low light intensity where the light signal is not that much larger than the noise from other peripheral components of 3-T image sensor. Likewise, the reset noise affects the depth accuracy of I-ToF sensor. Because the signal from reflected light is not accurate due to the reset noise from the conventional reset operation.

To overcome the reset noise problems from the conventional reset operation, active reset technique is proposed. The active reset technique is circuit technique for reset noise suppression. Active reset requires additional components such as an amplifier and switches for negative feedback loop. Then sampled reset noise at the photodiode or FD nodes would be suppressed with the negative feedback loop through the high gain amplifier. Also, the noise contributions from those additional components could be neglect compared with the suppressed reset noise.

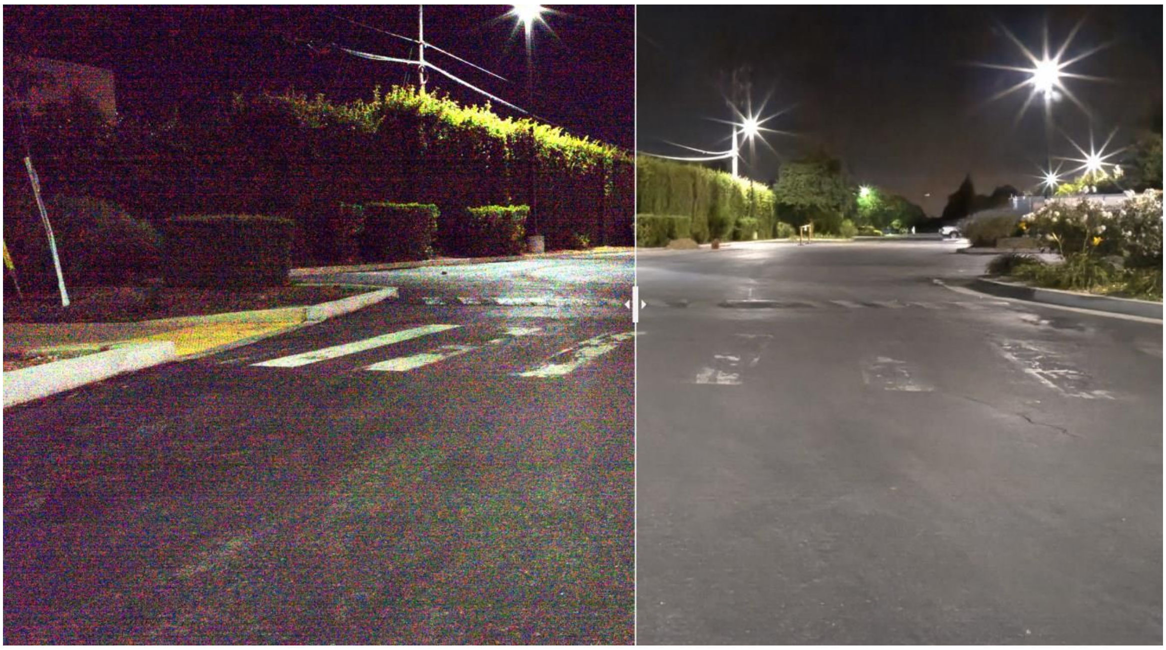
Operation of the active reset compromises with three steps. First, conventional hard reset is performed. Since the conventional hard reset can make the same initial state within few nano seconds, there is no residual electrons generated by the previous frame. Then the active reset is activated. The negative feedback helps to suppress the sampled hard reset noise. No matter how much noise is sampled on the photodiode or FD node in I-ToF sensor. Finally, slowly decrease the gate voltage of negative feedback switch to limit the noise attribution at the photodiode or FD nodes.

With three steps of active reset operation, the estimated reset noise can be inversely proportional to the square root of the gain of amplifier. It means that the reset noise can be suppressed up to 96 %. And the actual measurement results show that the reset noise is suppressed as 92% compared with the reset noise from conventional reset operation.

Chapter 1.

Introduction

1. Low Noise Image Sensor



(a) **(b)**

Fig. 1-1. (a) Noisy image under the low light (b) Low noise image under the low light

When the light intensity is low, the readout noise is dominant in that circumstance. Then the image from the sensor may be degraded by noise. As figure 1-1, these images are taken at the same time and the same place. Figure 1-1. (a) seems noisy due to the noise. Otherwise figure 1-1. (b) seems more clearer than the figure 1-1. (a). These figures show that the quality of images under the low light intensity would suffer from the noise of image sensor itself.

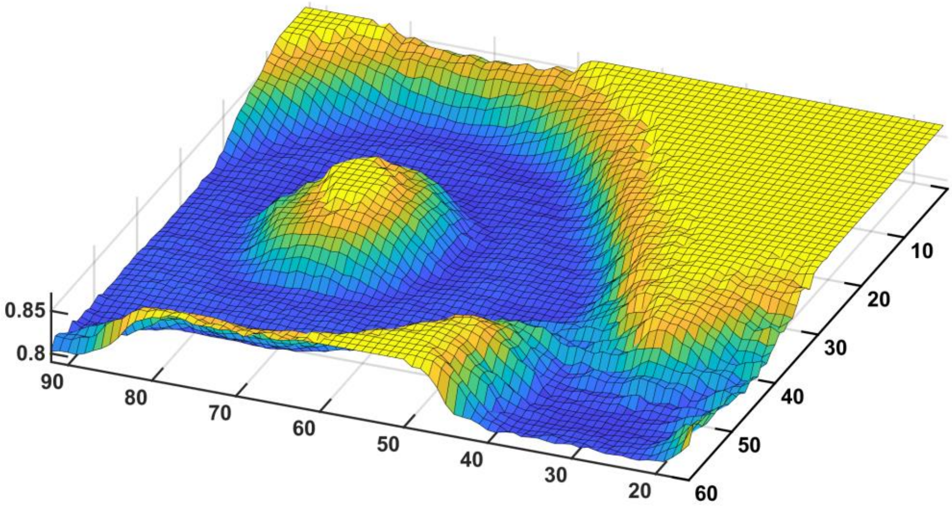


Fig. 1-2. Depth image of indirect ToF sensor

This phenomenon takes place in the indirect time-of-flight sensor (I-ToF). For I-ToF sensor with the high accuracy, set aside background light by external light source, I-ToF sensor should distinguish small number of photons from the reflected light which is signal from target object. Ideally, I-ToF sensor can discriminate a single photon.

However, in realistic case, the received light can be overwhelmed by noise from I-ToF sensor itself. As a result, the depth image can have noisy parts where in the border line of objects and even in the same distance plane as figure 1-2. Those places in that depth image are suffered from the noise where the noise components from image sensor are dominant than the received signal.

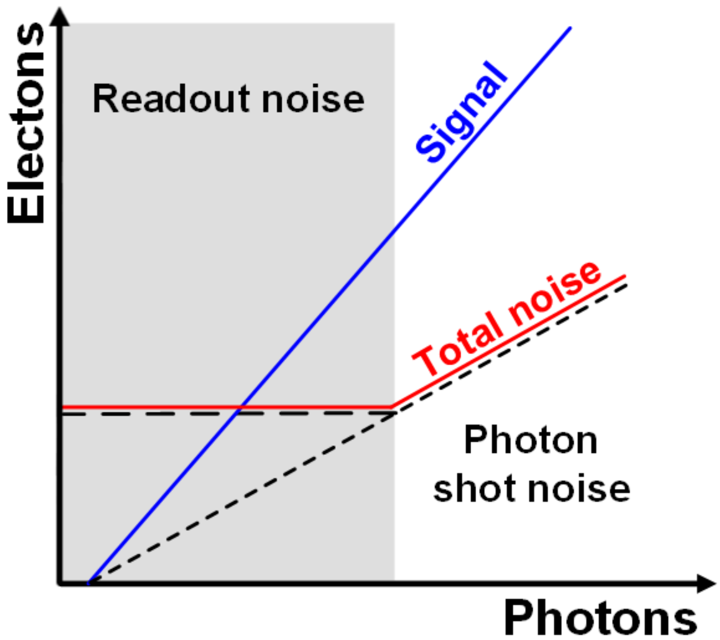


Fig. 1-3. Incident photons with electrons

Figure 1-3 shows incident photons with electrons on the image sensor. When the photons come into the photodiode, photodiode converts photons to electrons. The small number of electrons means that less photons are collected by low light condition which means low light intensity within a given time.

When the signal is low under the low light intensity, the readout noise from image sensor would be dominant, not photon shot noise which is proportional to the square root of the number of incident photons. That is why the photon shot noise is not dominant in that circumstance.

However, when collected photons are increased by increased exposure time or high light intensity, photon shot noise would take the dominant in total noise. At the point of view of signal, signal can be distinguished from the point where signal meets the total noise line. In that point, signal can be identified from the noise. It means that the red dotted noise line in figure 1-3 limits dynamic range of image. To break this limit under the readout noise dominant section is lower the red dotted line.

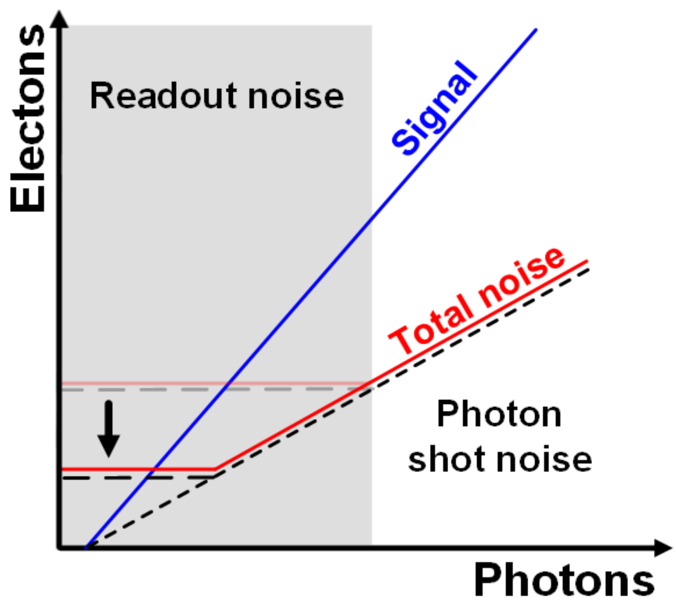


Fig. 1-4. Readout noise suppression on image sensor

Figure 1-4 shows that the red dotted line is lowered by suppressing the readout noise. In that situation, the signal is higher than the total noise floor. Now image sensor can identify signal from signal under the low light intensity condition without increasing the exposure time. Also, it is good for I-ToF sensor that depth accuracy would be increased that may lead to acquire more accurate depth image.

But in high intensity situation, the photon shot noise is inevitable. The only thing what we can do is sampling many times to suppress shot noise to averaged out. That is why the role for noise suppression is getting more critical to handle the readout noise by employing adequate circuit techniques. Before we suppress the readout noise, what we have to do first is that we classify and identify the noise in image sensors including pixel itself and the readout circuits themselves.

2. Noise Image Sensor

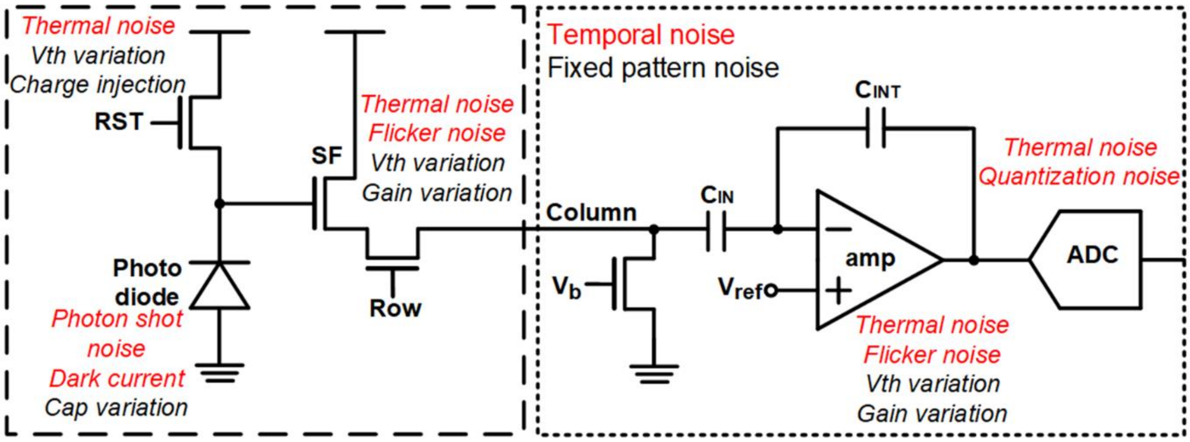


Fig. 1-5. Noise in image sensor

There are many noise sources in the image sensor. Two types of noise are existed in the image sensor. Those are temporal noise and fixed pattern noise. Temporal noise is random noise which cannot be predicted the exact value by its randomness. Otherwise, the fixed pattern noise is literally fixed as constant value, not random. Actually, the fixed pattern noise itself is also hard to expected. But it is easy to know the exact value of fixed pattern noise by measurement.

2-1. Fixed pattern noise

Fixed noise is normally caused by mismatch due to process variation. In figure 1-5, reset transistor RST, source follower SF and amplifier amp have Vth variation. Vth variation is typical mismatch due to process variation. Also gain variation and capacitive variation of photodiode are caused by process variation in the same manner of Vth variation.

But charge injection in reset transistor RST is a little bit different as mentioned above. Actually the charge injection is not fixed noise. When we try to turn off transistor, while it is turned on, charges in channel affect the final voltage state as noise by injected charges from the channel. Then why we deal with the charge injection as fixed noise is that the effect of charge injection can be calculated with peripheral factors and the calculated results is not different from the calculated results.

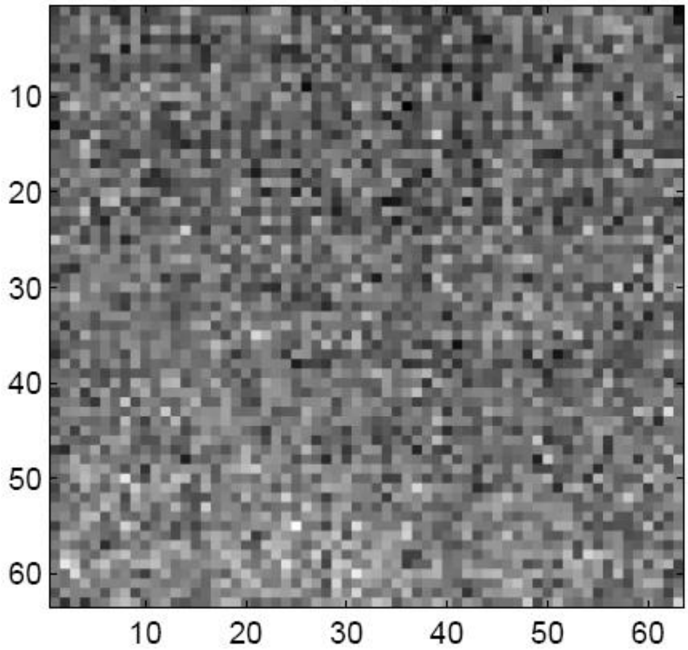


Fig. 1-6. Fixed pattern noise in pixel level

All of these fixed pattern noise components is also shown in image as patterns as figure in 1-6. That is why we call this as Fixed pattern noise FPN. Fortunately, we can eliminate this FPN easily. Because of its constant property, we can know the exact value of the amount of FPN at each point by measurement or the image.

To eliminate this FPN, we can do the digital processing step which is known as image signal processing ISP. Since digital output from the sensor always has a same value in dark state. So, lots of sampled images from dark state can make averaged value of each FPN at each point. Then we can use this average value to compensate FPN with ISP

2-2. Temporal noise

Temporal noise is not predictable due to its randomness. It is hard to expect that how much the noise exists and when the noise comes. Flicker noise at the source follower SF and amplifier amp could give low quality of image. Since flicker noise is occurred by the property of MOSFET itself. The dangling bond between the surface of oxide and the channel makes the trap and de-trap of electrons in NMOS, holes in PMOS. This trap and de-trap of majority carriers are happened with the recombination. That results in the noise in MOSFET

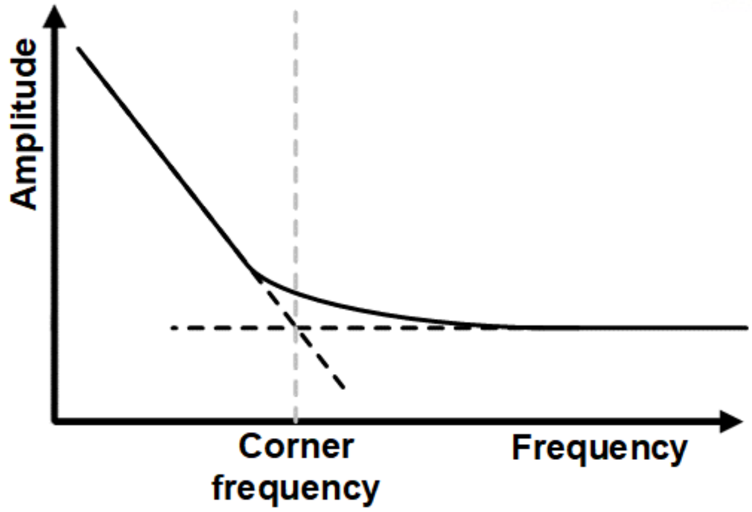


Fig. 1-7. Flicker noise in frequency domain

Figure 1-7 shows flicker in frequency domain. Flicker noise depends on its corner frequency. But in most case dominant region of flicker noise is in the low frequency. That why this is called as 1/f noise. Thanks to this property of flicker noise, we can easily suppress this noise by double sampling.

Image sensor can do sampling the reset value and the signal value separately. But this is not effective way to read out all pixel array in the sensor. So we do sampling the almost simultaneously. Read the reset value as right after the integration is finished or just before the readout signal value. Then we now have two samples reset value and signal value from one pixel.

Since double sampling frequency is much faster than the corner frequency, we can deal with the flicker noise as almost DC value. We now can make an equation below including with flicker noise.

$$(V_{reset} + FN) - (V_{signal} + FN) = V_{reset} - V_{signal}$$

Other temporal noise in image sensor is the dark current in photodiode. Dark current is that the photodiode flows the photocurrent without any incident light. Reasons for generating the dark current are leakage current and surface current. We can overcome dark current as employing pinned photodiode PPD. The pinning layer of PPD consumes all dark electrons which make dark current.

Quantization noise from ADC is also temporal noise. The solution for suppression quantization noise is very simple. By employing the high resolution ADC, the noise floor due to the quantization noise becomes lower than the noise floor from other temporal noise contributors.

The last and the most important temporal noise in image sensor is thermal noise. Thermal noise is pure white noise which has a zero mean in frequency domain. As its name, it is proportional to the temperature. Figure 1-5 shows that the thermal noise contributors are reset transistor RST, source follower SF, amplifier amp and ADC.

Source	# of Noise e-	Relative value
RST	20~50	High
SF	1~10	Low
Amplifier	1~10	Low
ADC	1~10	Low

Fig. 1-8. Typical value of thermal noise

The typical values of thermal noise in image sensor are known as figure 1-8. This figure shows that the reset transistor RST is the main noise contributor and other contributors are relatively low. Even if those thermal noise are independent and added up, still reset transistor RST takes a large portion of them.

Except thermal noise of reset transistor RST, those minor contributors are also called as thermal noise of readout integrated circuit. Since these temporal noise affects during the readout of signal and reset.

Chapter 2.

Reset Noise in Image Sensor

1. Pixel operation

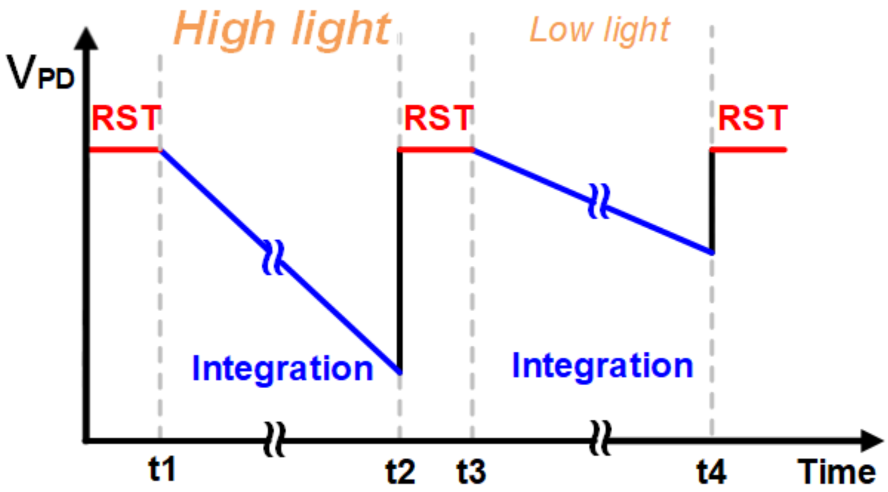


Fig. 2-1. Incident light with voltage of the photodiode

It is important to know that how does the pixel operate and how does the reset noise affect in the image sensor. Photodiode has depletion region and in that depletion region, generated electrons by incident photons are recombined. Since it acts like discharging of a capacitor, we can do modeling the photodiode as a capacitor. When the light comes in the photodiode, electrons are generated. The voltage of capacitor is falling due to these electrons as figure 2-1. When the image sensor is placed under the high light intensity, the voltage would be lower than the under the low light intensity in same integration time. Because the voltage of capacitor is proportional to the intensity of the incident light.

At the end of the photon incident phase, we should have to do reset for the next operation. To eliminate generated electrons in photodiode, we should apply reverse bias to the photodiode to drag electrons to VDD. as applying high voltage to the gate of RST. But due to the thermal noise, sampled voltage is not clear as VDD line. This result in that sampled V_{RST} on the photo diode is random with time.

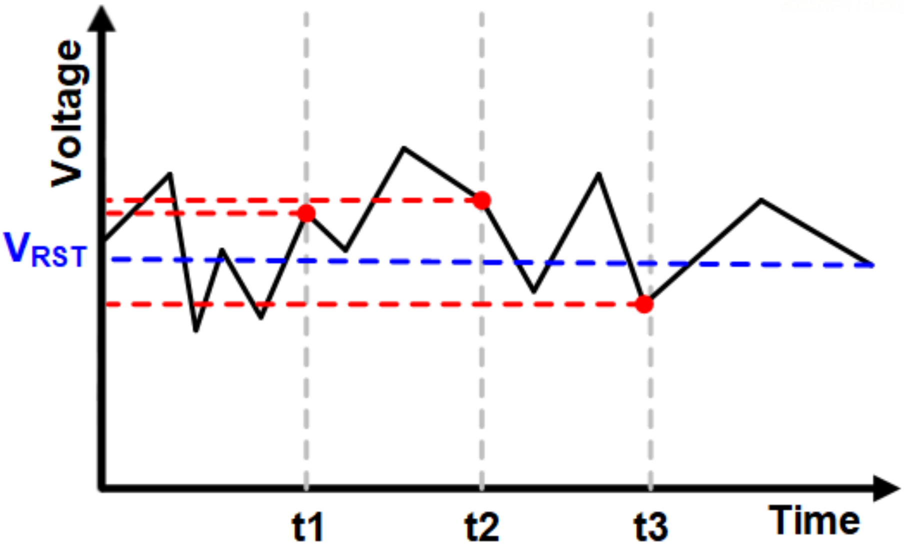


Fig. 2-2. Reset sampling with time

Figure 2-2 is time verses V_{RST} plot. As we have modeled photodiode as a capacitor, we can do sampling the voltage by applying voltage at the gate of reset transistor. And this plot shows that we cannot sample the clear reset voltage due to the random thermal noise. Every time we are trying to sample the reset voltage, we actually do sampling the different reset voltage in different time which is expressed as this $V_{RST} \neq V(t1) \neq V(t2) \neq V(t3)$

2. Conventional reset operation

2-1. Hard reset

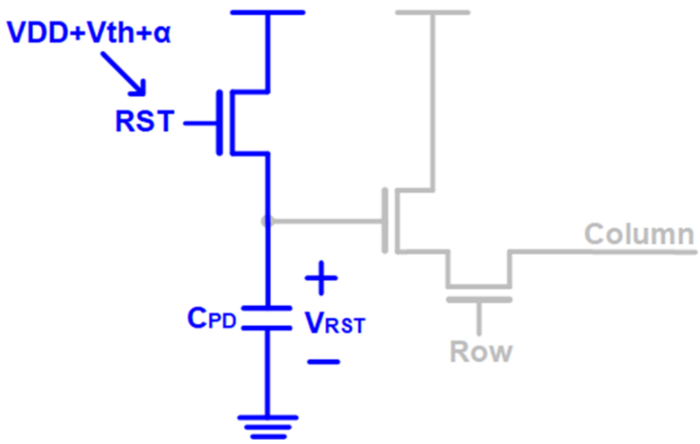


Fig. 2-3. Hard reset operation

Hard reset operation is that the gate of reset transistor is applied to ($VDD + V_{th} + \alpha$) as figure 2-2. At the initial state, applied voltage to the reset transistor would follow this condition $V_{GS} - V_{th} = VDD + \alpha - V_{PD}$ and $V_{DS} = VDD - V_{PD}$. If so, no matter how the previous voltage of V_{PD} does not matter. Because of the extra voltage α, reset transistor RST always falls into the triode region as $V_{GS} - V_{th} > V_{DS}$.

At the steady state, applied voltage to the reset transistor would follow this condition $V_{GS} - V_{th} = \alpha$, and $V_{DS} = 0$. With this condition, there is no more current flowing through the reset transistor and photo diode.

At the intial stata, hard reset can flow on currnet on the photodiode throgh the reset transistor. This on currnet makes short reset time within few nano second, also eliminates all residual electrons in the photo diode no matter how much electorns are remained. So there is no need to worry about image lag. It is totally indepent of the previous frame.

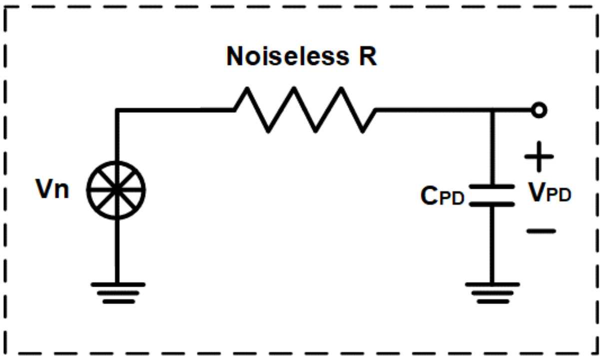


Fig. 2-4. Equivalent small signal model

Then we are looking into thermal noise due to the hard reset operation. To analysis noise of hard reset, the equivalent small signal model is required as in figure 2-4. As the reset transistor RST operates in the triode region, reset transistor RST has on resistance in the triode region. So the equivalent small signal has thermal noise voltage source Vn, noiseless resistor and photodiode capacitance C_{PD}.

First, we have to establish the transfer function of Vn and V_{PD} in frequency domain. To know how the noise is transferred to V_{PD}. By simple voltage division of noiseless R and C_{PD}, we can get the noise transfer function as follow [1].

$$V_{PD} = \frac{V_n}{\frac{1}{C_{PD} * s} + R}$$

$$H(S) = \frac{V_{PD}}{V_n} = \frac{1}{1 + R * C_{PD} * s}.$$

As we already knew that the noise voltage of resistor is 4kTR, What we have to do is to integrate the square of this transfer function in all frequency domain. Because the thermal noise is white in all frequency domain. Then multiply the noise voltage of a resistor which is 4kTR.

$$\overline{V_n^2} = 4kTR * \int \left| \frac{1}{1 + R * C_{PD} * 2\pi f} \right|^2 df = \frac{kT}{C_{PD}}$$

The noise power where sampled at the photodiode is kT/C_{PD}. Surprisingly the sampled noise power is independent of the resistance R. Aslo it has quite large noise power due to small capacitance of the photo diode. That is why the reset thermal noise is the most dominant term in the image sensor compared with other thermal noise contributors.

2-2. Soft reset

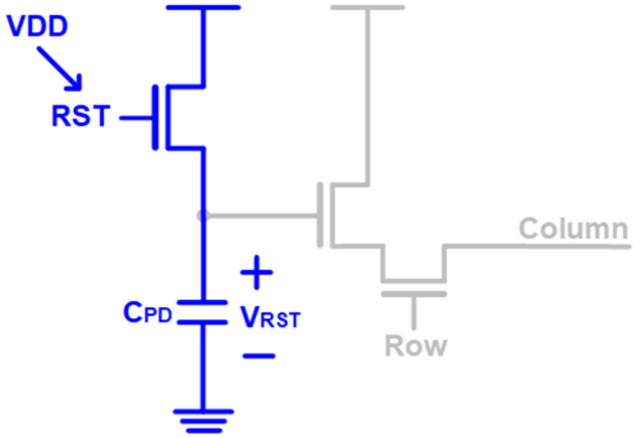


Fig. 2-5. Soft reset

Another conventional reset operation is soft reset. The difference between the hard reset and the soft reset is that the applied voltage at the gate of reset transistor is VDD. At the initial state of soft reset, reset transistor would follow this condition $V_{GS} – V_{th} = VDD –V_{th} – V_{PD}$ and $V_{DS} = VDD - V_{PD}$. Then the reset transistor can be either regions, triode region or sub-threshold region. It is solely depending on the previous state. And at the near steady state, the reset transistor would follow this condition $V_{GS} \approx V_{th}$.. With this condition, the reset transistor definitely goes into the sub-threshold region.

As mentioned above the initial state is solely depending on the previous state. Actually, it does matter because region where the reset transistor falls in effects the overall reset time. In sub-threshold region, flowing current is almost off-current which is very small amount of current comparing with the on-current. So the soft reset does not offer the enough time to eliminate residual electrons within same reset time of hard reset. It means that the soft reset requires more time to reset over few micro seconds. Also it can cause image lag depends on the previous frame. When the previous frame has exposed under the high light intensity or exposed long time, residual electrons affect the present frame.

About the noise in soft reset, since the soft reset operates in the sub-threshold region where current shot noise is dominant, noise is also varying with the time. That is why the soft reset noise analysis would be done in the time domain, not in the frequency domain.

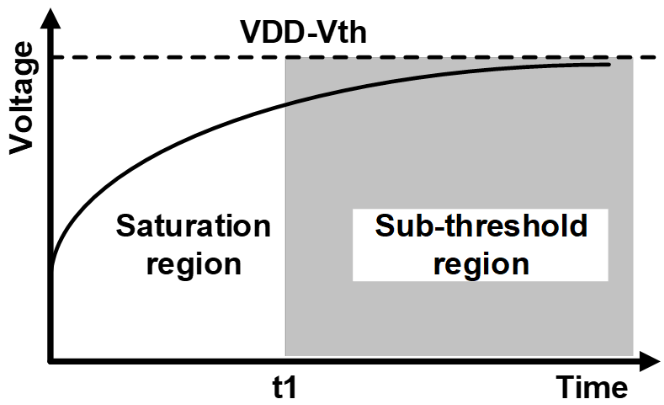


Fig. 2-6. Voltage plot of soft reset with time

Normally reset operation would be ended until the photodiode capacitor and the reset transistor RST settled down. But, in reality, settle time is over the milli second. This is very long time for pixel array to reset all the pixels. For moderate video application allowed time for reset is within few micro second. To meet this time confinement, the soft reset will be done in non-steady state within allowed time as shown in the figure 2-6.

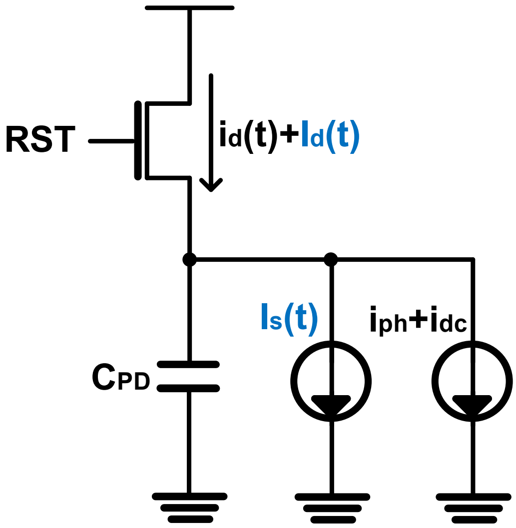


Fig. 2-7. Time domain analysis model for soft reset

As mentioned before, the noise analysis of soft reset would be conducted in time domain, since reset operation is done in non-steady state where time is varying. In figure 2-7. we can see the drain current in reset transistor, shot noise current in parallel with photo diode, also with the photo current and dark current. In the non-steady state, drain current is much larger than the other current. These current sources are the most dominant current than the others. Then we can establish time domain equation only including the drain current, sampled noise voltage and reset voltage on the photodiode neglecting other current source [1].

$$\text{Transconductance of total transistor } g(t) = -\frac{di_d}{dv_{ph}}$$

$$I_n(t) = C_{PD}\left(v_{ph}(t)\right)\frac{dV_n(t)}{dt} + g(t)V_n(t)V_n(t)$$

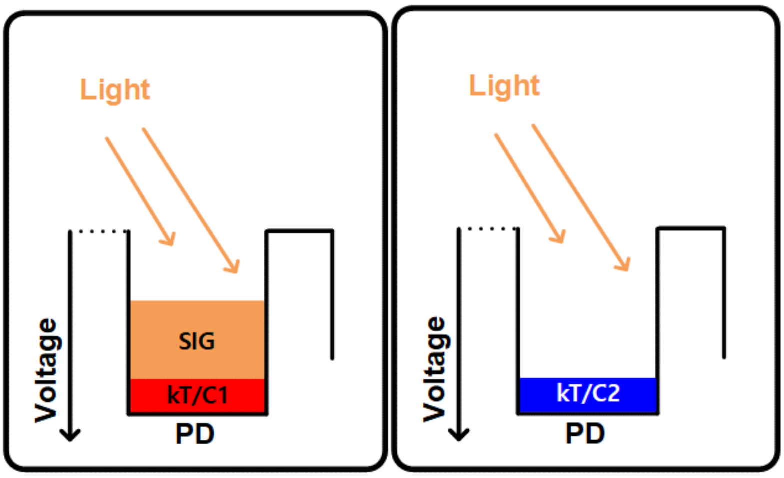
$$= \int_0^{t_r} \frac{I_n(\tau)}{C_{pd}(\tau)} \exp(-\int_\tau^{t_r} \frac{g(\tau_0)}{C_{pd}(\tau_0)} d\tau_0) d\tau$$

$$\overline{V_n{}^2} = \int_0^{t_r} \frac{q i_d(\tau)}{C_{pd}{}^2} \exp(-2\int_\tau^{t_r} \frac{g(\tau_0)}{C_{pd}(\tau_0)} d\tau_0) d\tau \cong \frac{1}{2}\frac{kT}{C_{pd}}$$

The results show that the sampled noise power in photo diode is halt of kT/C. In aspect of voltage, 30% of thermal noise has been improved. This is trade-off with the image lag. Implement of the soft reset needs to take a consideration of which one is dominant with image lag problem.

2-3. kTC noise in 3-transitor image sensor

All the image sensors shown above except I-ToF is 3-transistor image sensors. 3-transistor(3-T) means that literally the pixel consists of 3 transistors. To operate image sensor, two steps are required. One is integration of light at the photodiode and the other is reset the photodiode.



(a)integration (b) reset

Fig. 2-8. (a)integration (b) reset

Normally, 3-T image sensor integrates the light and readout the signal which is converted to the voltage after then photodiode is reset and readout the reset voltage. These two operations give us (Vreset - Vsignal) which is shown as image in a single pixel. During the integration, 3-T image sensor has reset thermal noise as kT/C1 which is caused by reset operation RST1.

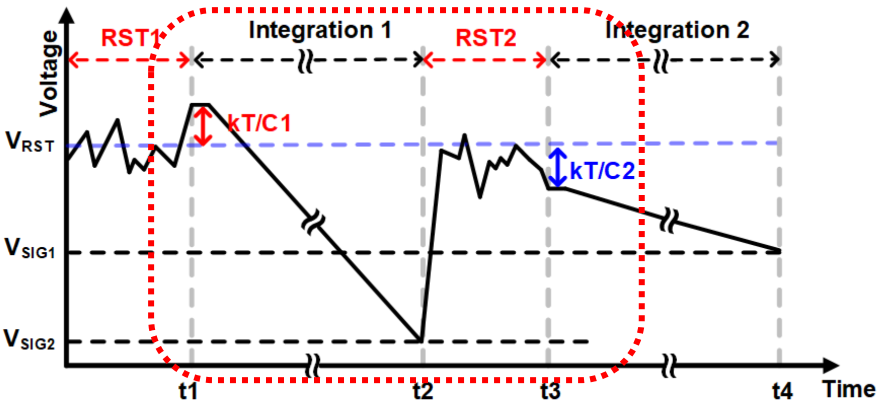


Fig. 2-9. Timing diagram of 3-T image sensor

But 3-T image sensor takes sampling the following reset voltage which is uncorrelated with the kT/C1 as figure 2-8. and figure 2-9. This sampling method seems weird. But this is unnecessarily to make efficient 3-T image sensor. As the integration needs to take about few milli second. That is long time for image sensor and for holding charges. When we do sampling of correlated reset signal with reset noise, the image sensor has to get the frame memory to store the reset voltage as long as few milli seconds. This is not effective way for cost and area. So the typical 3-T sensors do not have such a memory.

2-3. kTC noise in 4-transitor image sensor

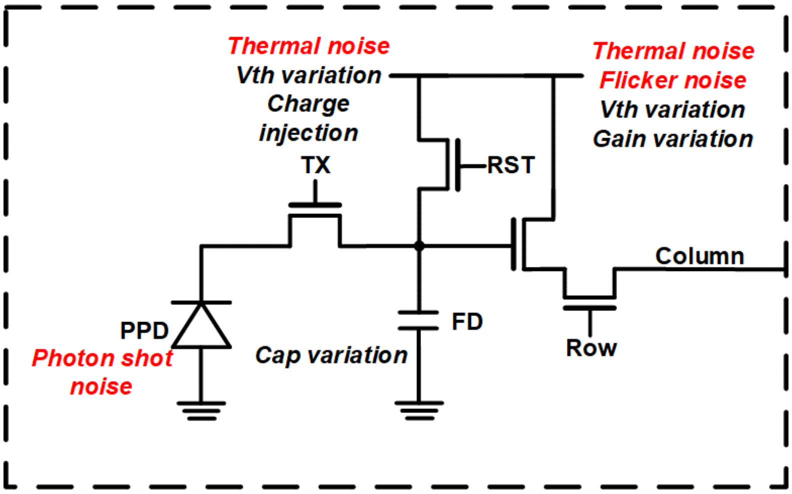


Fig. 2-10. 4-T image sensor with noise

A 4-T image sensor consists of 4 transistors and has almost same noise issues in pixel as figure 2-10. But the major difference between 3-T image sensor is pinned photodiode PPD. By adapting PPD, pinning layer helps to eliminate dark electrons from photodiode. In 4-T image sensor, PPD integrates the electrons which is converted from incident photons. Collected electrons are transferred to the floating diffusion node which is called FD node by TX. Then the voltage is changed due to transferred electrons. This is simple introduction of 4-T image sensor [2].

Thanks to this operation, kTC noise of 4-T is eliminated. As before transferring the electron, reset the FD node first and readout reset of the FD node with reset kTC noise. And then charges are transferred on that kTC noise and readout signal of the FD node. Since two kTC noise are correlated, 4-T image sensor is free from the kTC noise.

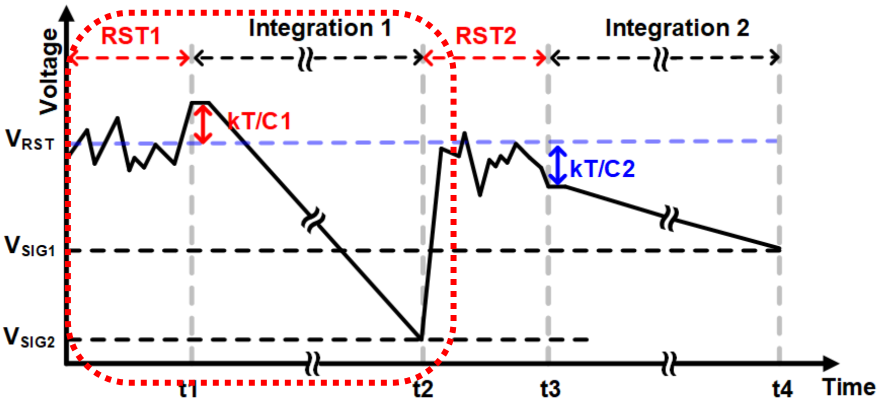


Fig. 2-11. Timing diagram of 3-T image sensor

Right after RST1 on the FD node, TX helps to transfer electrons from PPD to FD node. This operation is very fast. So, it can make correlation with kTC noise as shown in figure 2-11.

2-4. kTC noise in I-ToF sensor

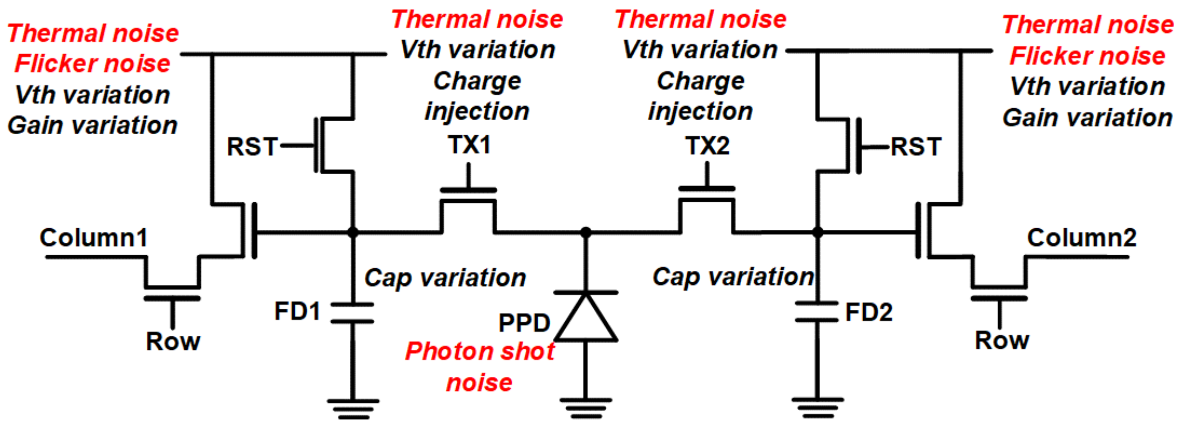


Fig. 2-12. Indirect-ToF sensor with noise

Basically I-ToF has same architecture with 4-T image sensor. So I-ToF pixel has same noise issue as 4-T pixel as figure 2-11. But the difference with 4-T image sensor is that FD node acts like a memory. When the modulated light comes in to the PPD, synchronized with the modulated light TX1 and TX2 transfer electrons to each FD1 node and FD2 node. Then the integrated electrons in each FD node has different voltage. Using the voltage difference of two FD nodes, we can detect phase difference of the modulated signal. That difference converted into depth image [3].

Before the integration, I-ToF also needs to reset the FD nodes. Inevitably uncorrelated kTC noise is sampled in each FD node. And then integration is stated with the modulated light. When the integration is finished, each FD node has signal and reset kTC noise. Since we do the depth calculation based on this voltage, I-ToF sensor also suffers from same kTC noise.

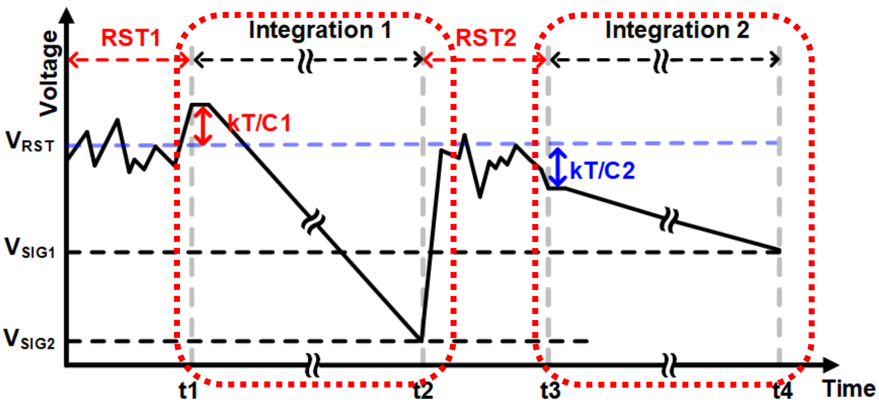


Fig. 2-13. Timing diagram of I-ToF sensor in FD1

Figure 2-12 shows that FD node integrates the signal on kTC noise. I-ToF sensor also has a long integration time. So it has same problem with the 3-T image sensor. Thermal noise results in error of depth calculation to I-ToF sensors

Chapter 3.

Proposed Active Reset Technique for Reset Noise Suppression

1.Active reset

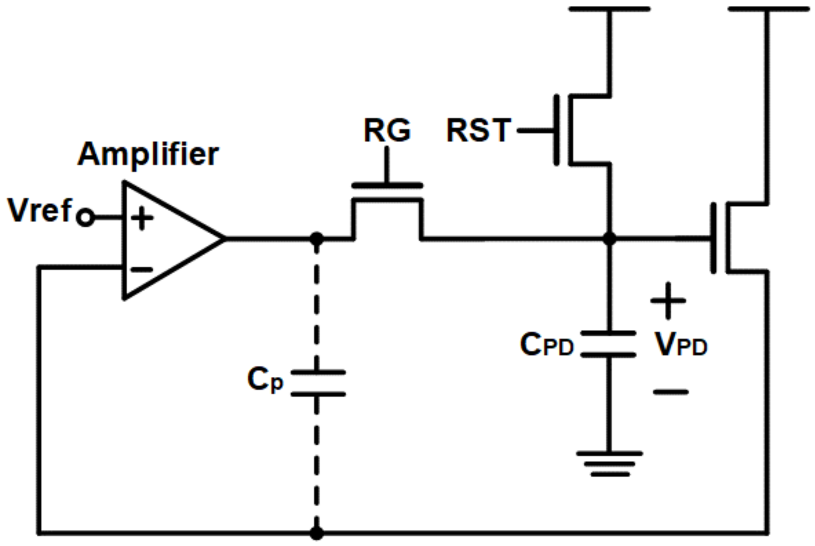


Fig. 3-1. Pixel with active reset circuit

Active reset is a circuit technique to suppress the thermal noise from conventional reset operation. Since 3-T image sensor and I-ToF sensor have a problem with the reset thermal noise, active reset can improve the SNR under the low light condition and improve the depth accuracy.

Figure 3-1. shows that the pixel of 3-T image sensor with active reset circuit. Unlike normal pixel of 3-T image sensor, active reset circuit has more components which are amplifier and reset gate switch RG. With these additional components, active reset can make the negative feedback and suppress the sampled reset kTC noise on photodiode [4] [5].

Brief operation sequence is as follows. Conventional hard reset would be done in first. By doing conventional hard reset, the residual electrons in the photodiode are eliminate within few nano seconds. That also helps to do make same initial condition when the operation begins. Then the negative feedback is set through the amplifier and reset gate switch RG. Due to the negative feedback, the sampled kTC noise from hard reset is suppressed and other thermal noise from additional components also can be suppressed.

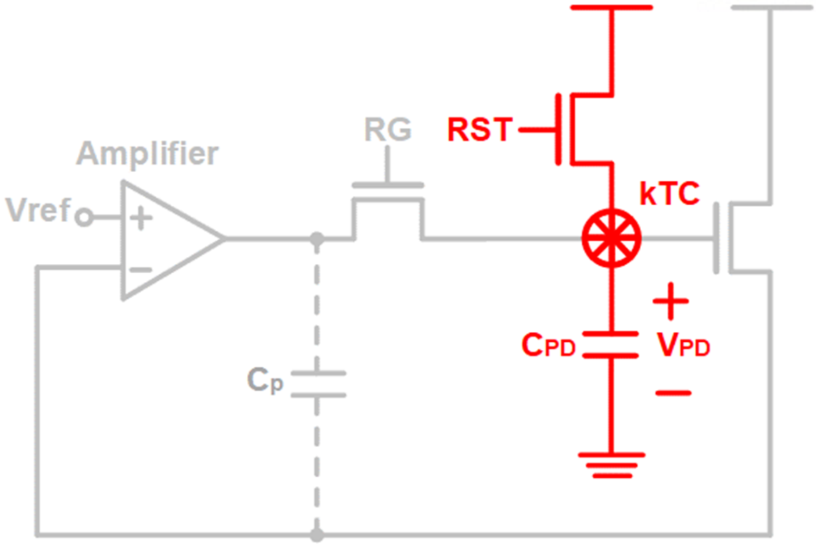


Fig. 3-2. Hard reset operation

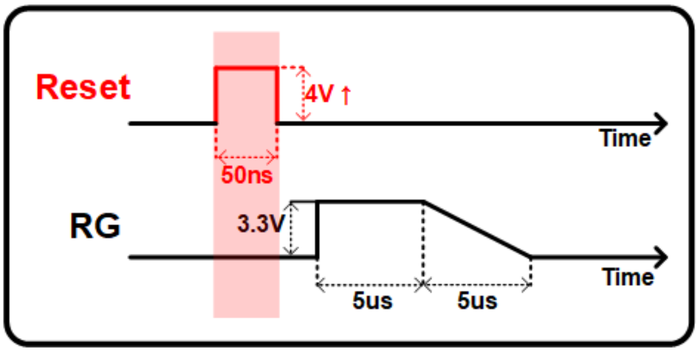


Fig. 3-3. Timing diagram for active reset operation

The hard reset operation is done as figure 3-2. All other components such as amplifier, reset gate switch RG and source follower would not involve in hard reset operation, Only the reset transistor RST and photodiode are working by flowing on-current through the photodiode as following the timing diagram of figure 3-3.

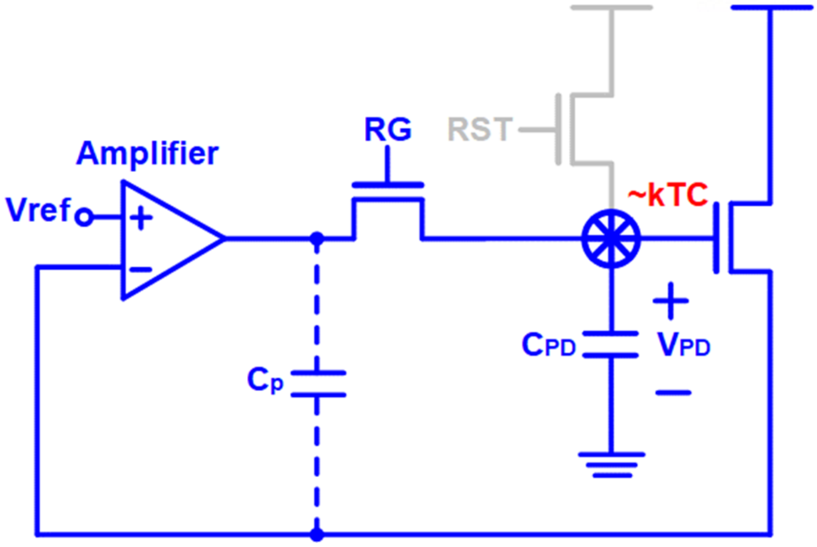


Fig. 3-4. Negative feedback mode

After the hard reset, the reset gate RG is turned on to make negative feedback as figure 3-4. And the gate voltage of reset gate RG is slowly decreased with time as following the timing diagram of figure3-3. Then, like a switch operation, the reset gate RG is slowly turned off which results in the break of the negative feedback loop and active reset operation would be done with lower sampled kTC noise.

2. Time domain noise analysis of active reset

For theoretical noise analysis of the active reset, what we have to do is time domain noise analysis. Because the sampled the kTC noise on the photodiode itself would be decreased with time through the negative feedback. Then the equations are derived from the circuit in figure 3-4.

Before getting into the analysis, voltage V consists of two parts. One is deterministic or averaged voltage Va and noise component v [6]. As we can express the voltage V, V = Va + v. For the ideal circuit, there is no noise on every component. Then the current would flow from the reset gate RG to photodiode without any noise current and current from output node of amplifier. The equation from this current flow is simply derived with KCL at the V_{PD}.

$$\frac{V1(t) - V_{PD}(t)}{R_{RG}} = C_{PD} * \frac{dV_{PD}(t)}{dt} + i_n(\mathrm{t}) \cdots (1)$$

The equation above shows that the current flow in ideal case. Actually, the current flowing through the reset gate RG is subthreshold current. Current equation expressed as ohm's law could be replaced as subthreshold current equation as below.

$$I_o e^{-\beta V1} = C_{PD} * \frac{dV_{PD}(t)}{dt} + i_n(\mathrm{t}) \cdots (2)$$

Where the $\beta = \frac{q}{mkT}$, $V_{GS} = V_G - V_S \approx V1$. And the voltage V1 is determined by output of the amplifier.

$$V1(t) = A(Vref - V_{PD}(t)) \cdots (3)$$

Since the equation consists of two parts, average term and noise term, average voltage of equation (2) will be

$$I_o e^{-\beta V1\_a} = C_{PD} * \frac{dV_{PD\_a}(t)}{dt} \cdots (4)$$

The average term is noiseless term that the equation with no noise current $i_n(t)$

Now we can substitute equation (4) to ideal equation. Then we can have equation (3)

$$V_{PD\_a}(t) = \frac{\beta AVref - \log\left(\beta A\left(V_{PD_a}(0) + \frac{I_o}{C_{PD}}t\right)\right)}{\beta A} \cdots (5)$$

The result shows the averaged term of the voltage of photodiode. With this result, the noise term can be expressed through equation (5) and equation (6)

$$I_o e^{-\beta A(Vref - V_{PD\_a}(t) - v_{PD}(t))} = C_{PD} * \frac{d(V_{PD\_a}(t) + v_{PD}(t))}{dt} + i_n(\mathrm{t}) \cdots (6)$$

As mentioned above, voltage term can be separated with the noise term as $V_{PD}(t) = V_{PD\_a}(t) + v_{pd}(t)$.

Substitute equation (6) into equation (5). The solution of sampled noise on the kTC noise now can be written as

$$< V_{PD\_n}(t) >^2 \approx \frac{kT}{AC_{PD}}$$

This is the result of suppressed reset noise. Compared with conventional hard reset noise, gain is decreased with the gain of amplifier. Since it is noise power, actual decreased noise voltage is proportional to square root of the gain of amplifier.

Intuitionally, the sampled reset noise suppressed due to its negative feedback. The assumption to solve the equations in time domain is that the feedback circuit has ideal source follower. This ideal source follower can make the feedback loop gain as 1. When the feedback loop gain is 1, $\beta = 1$. The equation would be

$$< V_{PD\_n}(t) >^2 \approx \frac{1}{1 + A\beta}\frac{kT}{C_{PD}} = \frac{1}{1 + A}\frac{kT}{C_{PD}}$$

This means that the reset noise kTC is suppressed by the negative feedback loop gain. Those two results from time domain analysis and from intuition are same. The higher amplifier gain gives more suppression reset noise. With the results from time domain noise analysis, we can have estimation results from the expected values of typical image sensors. ~

Expected values

Property	Value	Unit
C_{PD}	$5.5*10^{-15}$	F
C_p	~0	F
R_{RG}	$\sim\infty$	Ω
R_O	10^8	Ω
kT	$4.16*10^{-24}$	eV
$g_{m,amp} \approx G_M$	$10*10^{-6}$	S
$g_{m,sf}$	$50*10^{-6}$	S
A	1000	

Fig. 3-5. Expected values of typical image sensors

By applying values from figure 3-, suppressed sampled kTC noise power is

$$< V_{PD}(t) >^2 = \frac{kT}{A * C_{PD}} \approx 7.5 * 10^{-10} V^2$$

Compared with the previous kTC noise, the noise power has decreased as the gain of the amplifier which is 60dB, 1000 times decreased. Noise voltage is decreased as square root of 1000 which is approximately 31. If other thermal noise components are not dominant, this suppressed noise would be dominant.

3. Frequency domain noise analysis of active reset

If thermal noise from the other components is dominant, applying active reset technique could result in more noise contribution to the photodiode. So noise analysis of the other component should be conducted. To do so, noise analysis would be changed from time domain to frequency domain. Strictly speaking, this noise analysis is also conducted in time domain. Because the gate voltage applied to reset gate RG is time varying and the negative feedback loop is affected by reset gate RG. But for simplicity of analysis and clear point of view, frequency domain noise analysis would be conducted with approximation.

Before the noise analysis in frequency domain, noise contributors are defined. In pixel with active reset, there are three major noise contributors which are amplifier, reset gate, source follower noise as in figure 3- 6.

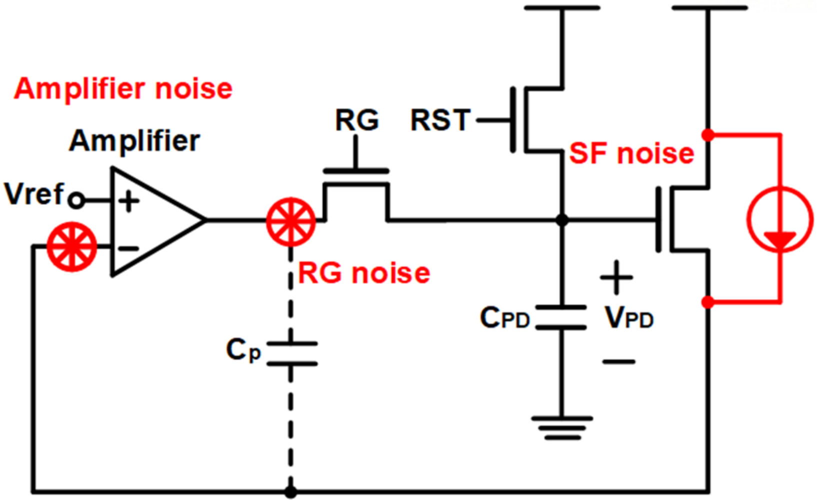


Fig. 3-6. Thermal noise contributors in pixel with active reset circuit

Typical way to analysis each noise contribution to the photodiode is done by superposition method. Since each noise contributor is independent each other, superposition method can be applied. But for simplicity, the noise analysis would be conducted as all noise source is merged to the noise source of the amplifier. This method cannot give us exact noise proportion of each components and only give us approximation noise.

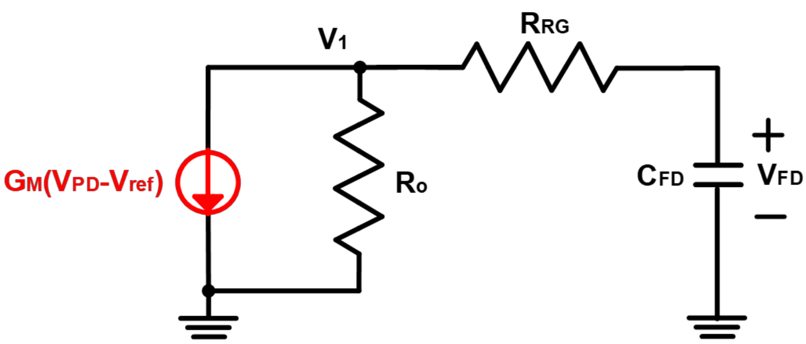


Fig. 3-7. Small signal model for noise analysis in frequency domain

Since all noise source is merged into amplifier noise, the noise source can be expressed in noise current of amplifier as figure 3-7. To establish the equations for solving noise in this circuit, KCL is applied to node V1 and node V_{PD}. Then two current equations are derived as below.

$$\text{i)}\quad \frac{V_{PD}-V_1}{R_{RG}} = G_M * (V_{PD} - V_{ref}) + \frac{V_1}{R_O}$$

$$\text{ii)}\quad \frac{V_1-V_{PD}}{R_{RG}} = V_{PD} * C_{PD} * s$$

Substitute equation (ii) into equation (i), we can get the noise transfer function from amplifier to photodiode.

$$H(s) = \frac{V_{PD}}{V_{ref}} \approx \frac{1}{1 + \frac{C_{PD}(R_o + R_{RG})}{A+1} * s}$$

Now we have noise transfer function. Since we merge noise sources which are independent each other. We can estimate the total noise on photodiode. With the expected value in figure 3-5, total noise on photodiode is

$$\overline{V_{n,PD}^2}$$

$$= \overline{V_{n,amp}^2} \int_{-\infty}^{\infty} |H(f)|^2 df + \overline{V_{n,sf}^2} \int_{-\infty}^{\infty} |H(f)|^2 df + \overline{V_{n,RG}^2} \int_{-\infty}^{\infty} |H(f)|^2 df$$

$$= \left(\frac{16kT}{3g_{m,amp}} + \frac{8kT}{3g_{m,SF}} + 4kTRRG\right) * \int_{-\infty}^{\infty} \left| \frac{1}{1+\frac{C_{PD}(R_o+R_{RG})}{A+1} *(2\pi f)} \right|^2 df$$

$$\approx 10^{-11} V^2$$

The meaning of this estimation result is that the noise from additional components is much smaller than the suppressed noise. Amplifier, source follower, reset gate RG thermal noise do affect small portion of total noise on photodiode.

$$\overline{V_{n,PD}^2}$$

$$= \overline{V_{n,amp}^2} \int_{-\infty}^{\infty} |H(f)|^2 df \, \overline{V_{n,sf}^2} \int_{-\infty}^{\infty} |H(f)|^2 df \, \overline{V_{n,RG}^2} \int_{-\infty}^{\infty} |H(f)|^2 df + \frac{kT}{AC_{pd}}$$

$$\approx 10^{-11} + 7.5 * 10^{-10} V^2$$

$$\approx 7.5 * 10^{-10} V^2 = \frac{kT}{AC_{pd}}$$

4. Proposed pixel level active reset sensor

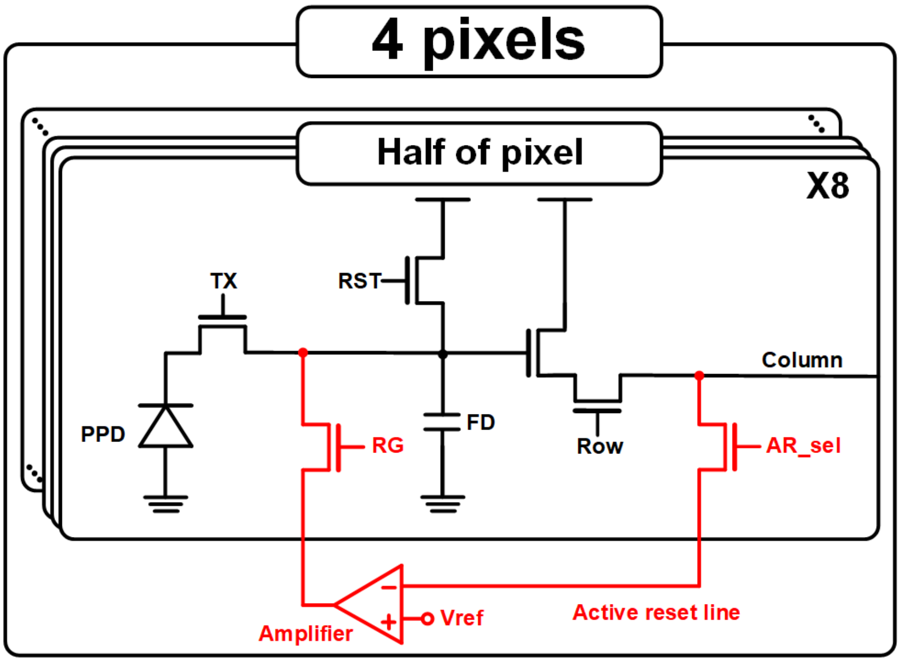


Fig. 3-8. Small signal model for noise analysis in frequency domain

The result from noise analysis confirms that the active reset can suppress the sampled reset noise and additional components can be neglected. Based on the analysis, we proposed I-ToF sensor with pixel level amplifier for low reset noise as in figure 3- 8. The purpose of this sensor is mainly focused on the verification of active reset technique. So proposed sensor is based on I-ToF but it can be used as 2D image sensor as 3-T image sensor to verify active reset in 2D image.

As amplifier is placed in pixel level in FSI process, amplifier is shared by 4 pixels. In spite of the shared amplifier structure, proposed sensor can do nearly pixel parallel active reset operation that is exactly 4 times slower than 1 pixel per 2 amplifier structure for two FD nodes. But much faster than column parallel structure.

Pixel level amplifier can alleviate the burden of load capacitance from parasitic capacitance of the active reset line. That feature also helps to alleviate design burden of amplifier. Because pixel level structure is highly suffered from the limitation of area for amplifier.

Since proposed sensor is based on the conventional I-ToF sensor, overall operation is same as the conventional I-ToF sensor as we have been designed. Only difference is that the reset operation with active reset technique. Due to the shared amplifier, active reset would operate four times for one row. Because each I-ToF pixel has two FD nodes in one pixel and the other two pixels which share amplifier are located in the other row.

To control the active reset operation and the row operation, row parallel driver makes the signals to control this logic by digital signal. But the gate voltage RG needs to be controlled by analog signal which is decreasing voltage. This signal is coming from the ramp generator placed in the next to the analog CDS block as shown in figure 3-9. And figure 3-10. is specification table of proposed sensor.

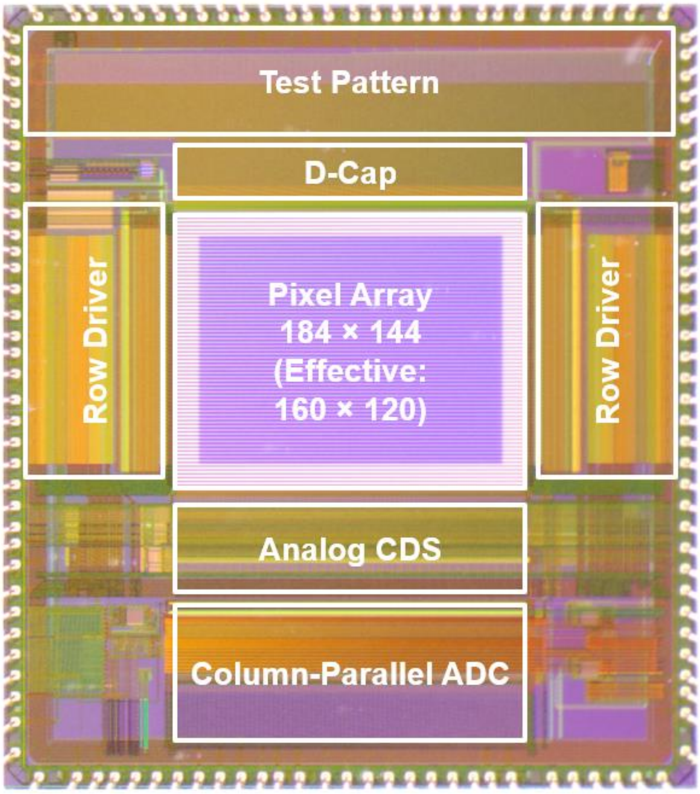


Fig. 3-9. Chip photograph of proposed sensor

Active reset sensor 1 specification	
Fabrication process	110nm FSI
Pixel resolution	184 x 144
Pixel pitch [um]	14.4um
Chip size [mm^2]	25
Supply [V]	3.3V / 1.5V
Frame rate [fps]	30
ADC resolution[bit]	10

Fig. 3-10. Specification table of proposed sensor

Chapter 4.

Measurement

1. Measurement setup

Digital signals to control proposed sensor are supplied by FPGA and received the digital output with labview system. Verification of the active reset technique is hard to verify by output images and to know exact value from output images themselves. To know exact value of reset thermal noise from measurement, we only have operated reset operation. Since proposed sensor has column parallel CDS array, we sampled two reset values by CDS which has switched capacitor circuit.

Two sampled reset value have uncorrelated reset noise. These reset noise components are not subtracted each other but added. Also measured reset noise is root mean square value. The measured results should be divided by square root of 2 for two sampled noise.

Proposed sensor has on-chip ADC which is 10-bit single slope ADC. But estimation result would be expected as small value. So we have amplified the reset value as 8 times by selecting feedback capacitor of switched capacitor in CDS. And we have used the off-chip ADC which is 12-bit pipe-line ADC. As mentioned in introduction, high resolution ADC helps to make lower the quantization noise.

The measurement has been conducted about 25 degrees Celsius and Off-chip ADC is 12-bit which has 340uV as 1 LSB. The number of sampled reset value is 1000. Reference voltage is 1.8V.

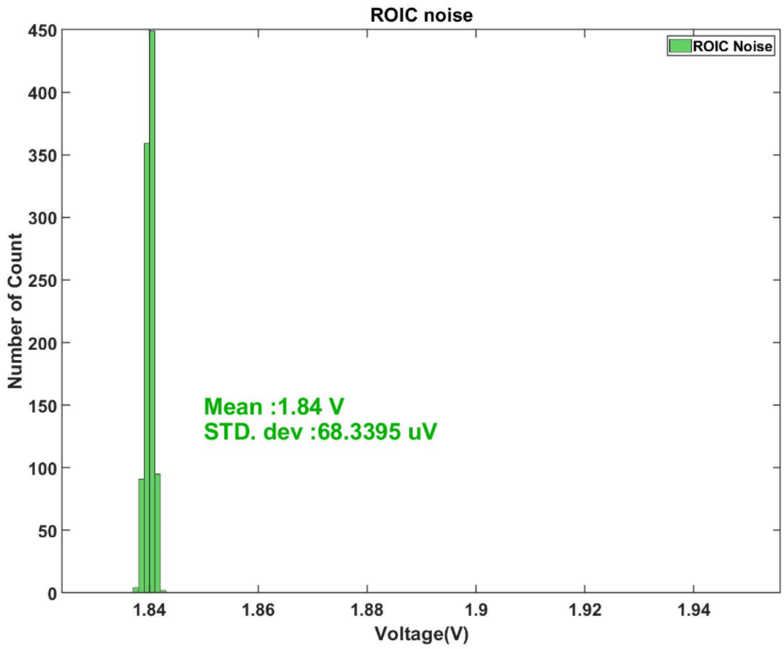


Fig. 4-1. ROIC noise of proposed sensor

2. Measurement results

2-1. ROIC noise

ROIC noise is coming from readout integrated circuits. The noise components are independent each other summed up by thermal noise chain. To do so, we can measure exact value of reset thermal noise by subtract ROIC noise.

The measured ROIC noise plot is figure 4-1. Mean value is the reference voltage of ADC and standard deviation is output referred thermal noise. ROIC noise is very small due to no reset thermal noise. Also, we can expect that the 4-T image sensor shows the same noise as the ROIC noise. Because the operation of 4-T image sensor can eliminate kTC noise from reset operation.

2-2. Hard reset noise

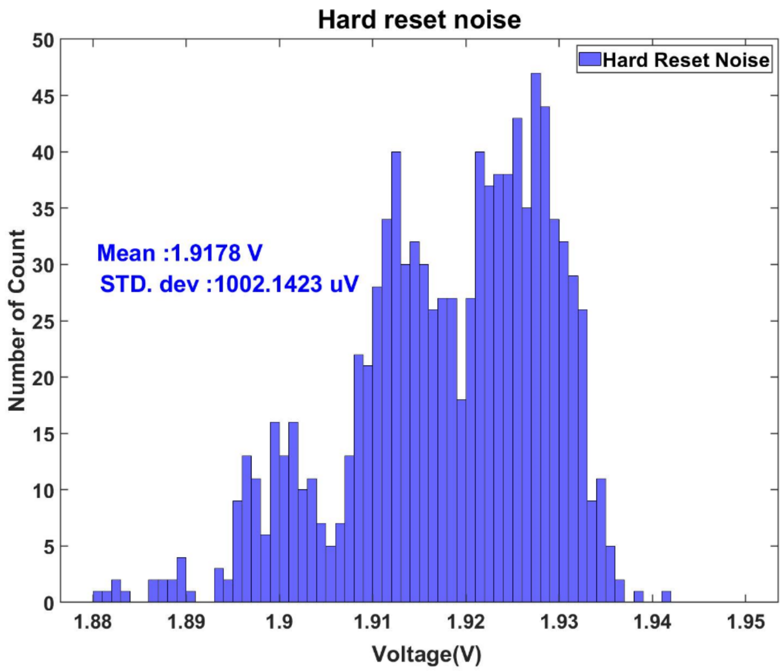


Fig. 4-2. Hard reset noise of proposed sensor

Hard reset noise as we estimate is 840uVrms. But the measured noise is 1002uVrms. Because the measure noise is including the ROIC noise. So the ROIC noise is subtracted from the measure noise. Measure noise is rms value and subtract ROIC is conducted in power spectral domain.

$$\sqrt{\sigma_{n,rst}^2 - \sigma_{n,ROIC}^2}$$

The reset noise would be 997uVrms which is larger than the estimation value 840uVrms. Mean value is 1.9V that is different from the reference voltage 1.8V. This may come from the process variation. Due to the process variation, offset can be differed from pixel by pixel or column by column.

2-3. Active reset noise

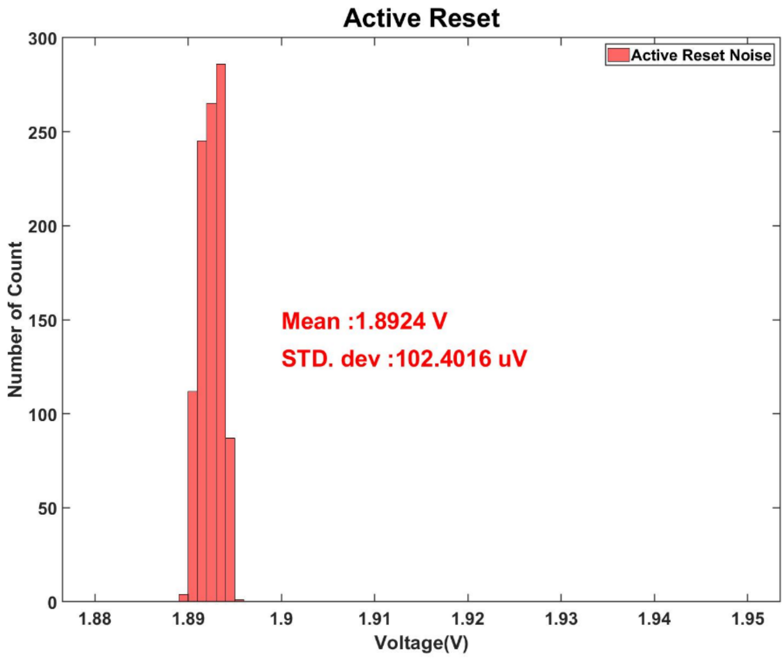


Fig. 4-3. Active reset noise of proposed sensor

Estimate thermal noise from active reset is about 27uVrms. But the measure noise is 102uVrms. This is also including ROIC noise as measurement result of hard reset noise. The active reset noise should subtract ROIC noise from measured result. The active reset noise is 76uVrms. It is a little be larger than what we expected as 27uVrms. But actual suppression rate is only 4 percent different. Since the sampled noise from hard reset is more than we expected, suppressed noise also could be larger than we expected. However, through the measurement, the effect of active reset is proved.

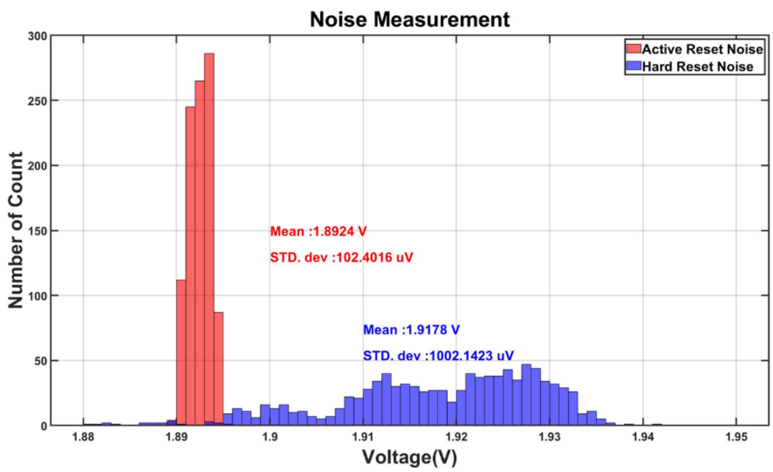


Fig. 4-4. Compared with hard reset and active reset

Reset Noise Suppression			
	Hard reset	**Active reset**	**Suppression rate**
Estimation value	$840\mu V_{rms}$	$27\mu V_{rms}$	**96%↓**
Estimation noise electrons	$29e^{-}$	$0.9e^{-}$	
Measured value	$997\mu V_{rms}$	$76\mu V_{rms}$	**92%↓**
Measured noise electrons	$34e^{-}$	$2.6e^{-}$	

Fig. 4-5. Comparison table of estimation and measured results

Figure 4-4. shows that active reset and the hard reset noise in same domain. Since hard reset has larger noise than the active reset, hard reset shows broaden voltage deviation. Figure 4-5. is comparison table of estimation and measured results. Hard reset noise is estimated as 840uVrms and it can be converted to noise electron using equation $Q_N=C_{PD}$ x V_N in FD node. Then the estimated number of noise electrons is 29 electrons. Measured hard reset noise is larger than estimated value. In the same manner, the measured number of noise electrons is 34 electrons for hard reset and active reset is 2.6 electrons. The equation $Q_N=C_{PD}$ x V_N is linear equation the suppression rate of noise electron is same in the voltage.

Chapter 5.

Conclusion

From the introduction, there are many noise components in CMOS image sensor. For example, fixed pattern noise and temporal noise are representative noise components not only in pixel but also in column parallel ROIC. As the fixed pattern noise components are easily eliminated by using image signal processing. Otherwise, the temporal noise components in image sensor are purely random. Such temporal noise can be classified as shot noise, flicker noise, dark current, ADC quantization noise and thermal noise. However, we can suppress other temporal noise component expect thermal noise.

Thermal noise component is existed in all image sensor components due to its random motion of electrons as CIS based on CMOS device. Especially the most dominant thermal noise of image sensor is the thermal noise from reset transistor. Since image sensor requires reset operation using reset transistor for continuous operation, photodiode or FD nodes should be reset. But reset voltage on photodiode or FD node is not same as the previous reset voltage value or next reset voltage value due to thermal noise from reset transistor. That thermal noise makes noisy output image. And this effect is getting worse under the low light intensity situations.

There are two typical reset operations. Hard reset is one of them. Applying high voltage to the gate of reset transistor drags electrons in the photodiode to VDD. So the photodiode can be operated in the same state as no residual electron. However, aspect of noise, we can model the reset transistor as a resistor and the photodiode as a capacitor. The simplified model is same as RC network that makes kT/C in all frequency domain. Since this kTC noise white noise and independent of sampling frequency, this noise can affect the output image. That is why the other reset operation, soft reset, was proposed.

Soft reset applies VDD to the gate of reset transistor. Then the reset transistor falls into subthreshold region and stop the reset operation before steady-state region. The remained noise would be the half of kTC noise. Now the kTC noise is half of the hard reset method, but the reset transistor operates in subthreshold region where the small current is flowing. The residual electrons can be existed in the photodiode.

To overcome the thermal noise, there are some circuit techniques for suppression. 4-T image sensor can suppress the kTC noise from reset transistor by its operation. Since 4-T image sensor does not use FD node as memory, correlated kTC noise can be canceled out. But 3-T image sensor has kTC noise in the photodiode that cannot be suppressed by its operation and I-ToF sensor also has same kTC noise as 3-T image sensor. Both sensors have in common that uncorrelated kTC noise remained in the photodiode or FD nodes. That is why the active reset technique had proposed to suppress kTC noise.

Proposed active reset technique consists of the high gain amplifier and reset gate switch RG with conventional pixel structure. Then the active reset makes negative feedback loop with the photodiode or FD nodes via amplifier and reset gate switch RG. First the hard reset is performed that eliminates all the residual electrons in the photodiode or FD nodes. Then the image sensor can start in the same condition independent of the previous state.

After the hart reset, reset gate switch is turned on. The negative feedback is now formed via amplifier. Until the negative feedback loop is settled down, the voltage applying to the gate of the reset gate switch holds constant voltage due to limited bandwidth of amplifier. Then slowly decrease the voltage applying to the gate of the reset gate switch to fall the reset switch gate into the subthreshold region. That limits the bandwidth of noise from active reset components.

To analysis thermal noise by active reset, we did time domain noise analysis and frequency domain analysis. During the negative feedback, the thermal noise is changing with time. So we can get the equation with time from circuits by KCL. And the other thermal noise components are known by frequency domain with small signal model of active reset circuit, since those components are the time independent during the active reset operation.

Theoretically, the sampled thermal noise on photodiode or FD node is suppressed about 96 % compared with the hard reset kTC noise. And the noise from amplifier, source follower and reset gate switch is quite small compared with suppressed noise that can be neglected. Also, by the measurement, the sampled thermal noise on FD node is suppressed 92% compared with the measured hard reset noise. In conclusion, thanks to the active reset, the sampled noise can be suppressed up to 96% in theoretically and 92% in measurement.

Chapter 6.

Further works

The measurement was implemented by selected pixels in pixel array. That results show that the effect of active reset from raw data. The reason why we measured the selected pixel is to verify affections of active reset. For verification of active reset, we must have to analysis of tendency from the selected pixels. So, the previous measurement was focused on tendency. Further works would be focused on acquisition of image from proposed sensor. This sensor can get not only 2D image but also 3D depth image.

2D image would be acquired under the low light condition about 10-lux that is same as dark night condition. We can compare two images under this condition. One image is acquired by hard reset. As we mentioned above introduction, signal is overwhelmed by noise when the light intensity is low. This is same quote as low light condition. Under that condition, signal is not discriminated with the noise.

However, the other image acquired by active reset shows the better quality of 2D images. Since the active reset can suppress thermal noise up to 92%. So, the expected results would be the same as fig1-1. The image from hard reset may suffer from noise under the low light and the image from active reset may overcome the noise that the reset noise is suppressed.

Since the proposed sensor is based on I-ToF sensor which is also suffered from reset thermal noise, we can compare the effect of active reset from depth image. Depth image acquired from previous I-ToF sensors has noise at the boundary and target placed in long distance as figure 2-1. When thermal noise exists in the depth image, the measured distance could be distorted. This distorted depth image shows incorrect depth information which is differ from the real distance of target object.

The property of thermal noise that is purely random may affect the precision of I-ToF sensor, since the noise may differ with time. With active reset, we can expect that the results would show less noise at the boundary and long distance target that means more clear depth image can be acquired with active reset operation. From the cleared depth image, we can expect that the non-linearity and precision also would show better performance than the previous I-ToF sensor.

We only mentioned proposed I-ToF sensor with active reset sensor which operates in pixel level. The fact that we proposed another active reset sensor which operates in column level. There are many differences from the first proposed sensor. First, the second sensor was fabricated in 90nm BSI process. The purpose of BSI process is for suppression background light.

Background light affects performance of I-ToF sensor. Because background itself is same as constant noise that can degrade the quality of image. So, background suppression is important to design accurate I-ToF sensor. To suppress background light, the analog memories are required. These analog memories help to cancel out background light by subtracting outphase signal and inphase signal. Then subtracted signal has no background light due to constant background light and this signal would be kept in those analog memories.

This proposed sensor adapts analog memories which are MIM capacitors in pixel level. And the active reset operates column level via column parallel amplifier. We can expect that the depth map can be acquired independent of the measurement environment when the light intensity is strong or weak. And the affections of active reset via column amplifier could be compared with the previous active reset sensor which has pixel level amplifier.

References

[1] Hui Tian, Boyd A. Fowler, Abbas El Gamal, “Analysis of temporal noise in CMOS APS.” Proc. SPIE 3649, Sensors, Cameras, and Systems for Scientific/Industrial Applications, Apr. 1999.

[2] Seong-Jin Kim, Sang-Wook Han, Byongmin Kang, Keechang Lee, James D. Kim and Chag-Yeong Kim, “A 3-D Time-of-Flight CMOS Image Sensor with Pinned-Photodiode Pixel Structure,” IEEE Electron Device Lett., vol.31, no.11, pp. 1272-1274, Nov. 2010.

[3] R. Lange, “3D Time-of-Flight distance measurement with custom solid-state image sensors on CMOS/CCD-technology,” Ph.D. Dissertation, 2000.

[4] Boyd A. Fowler, Michael Godfrey, Janusz Balicki, John Canfield, “Low-noise readout using active reset for CMOS APS,” Proc. SPIE 3965, Sensors and Cameras Systems for Scientific, Industrial, and Digital Photography Applications, May 2000.

[5] Lester J. Kozlowski, Giuseppe Rossi, Laurent Blanquart, Roberto Marchensini, Ying Huang, Gregory Chow, John Richardson, David Standley, “Pixel Noise Suppression via SoC Management of Tapered Reset in a 1920 x 1080 CMOS Image Sensor,” IEEE Journal of Solid-State Circuits, vol.40, no.12, Dec. 2005.

[6] Nobukazu Teranishi, “Analysis of Subthreshold Current Reset Noise in Image Sensors,” MDPI sensors, May 2016.